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The Design Characteristics of Inflatable Aluminized-Plastic Spherical Earth Satellites With Respect to Ultraviolet, Visible, Infrared and Radar Radiation

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An investigation was made to predict whether a hollow aluminized-plastic sphere in a terrestrial orbit at about 1000 miles altitude would be easily visible to the naked eye, would be a good reflector of radar waves, would be protected from deterioration of the plastic by ultraviolet radiation, and would assume acceptable extremes of temperature. It was found that a 2200 A thick coating of vapor-deposited aluminum on ¼-mil-thick mylar forming a 100-ft-diam sphere would probably meet all requirements regarding radiation as well as a maximum weight limit of about 100 lb.

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The Design Characteristics of Inflatable Aluminized-Plastic Spherical Earth Satellites With Respect to Ultraviolet, Visible, Infrared and Radar Radiation

Among the satellite experiments of interest is one involving the use of a large, lightweight, inflatable, plastic spherical shell.[1] It would be desirable for this satellite to be easily visible to the naked eye, to be a good reflector of radar signals, and to have a long lifetime in orbit. The satellite would then have a number of uses which need not be discussed herein.

In addition to meeting a maximum weight requirement and an approximate minimum size requirement, there were therefore four requirements involving electromagnetic radiation in the spectrum from the extreme ultra-violet to radar wavelengths, inclusive, that were desired to be met. These were:

1 That the satellite reflect sufficient visible radiation from the sun to be readily discernible by the naked eye when at an altitude of the order of 1000 miles.

2 That the satellite reflect radar waves as well as practicable.

3 That the plastic which formed the shell of the satellite be protected from deterioration by long-term exposure to the sun's ultraviolet radiation.

4 That the satellite assume, by virtue of its reflectivity to solar radiation and its emissivity in the infrared, an equilibrium temperature in sunlight that was not too high and in the earth's shadow that was not too low.

The purpose of the present paper is to describe the methods used and the results obtained in so designing the vehicle that it would, as far as was practicable, meet the four requirements involving radiation.

GENERAL CONSIDERATIONS

The spherical shape was chosen in order to provide a configuration that would not scintillate if the vehicle rotated or tumbled, as scintillation was undesirable for a radar reflector, and to provide a configuration for which there was no difficult orientation problem, as there would be for a concave mirror. To meet the weight limit, which was approximately 100 lb including the container, and at the same time to provide as large an object as possible, 1/4 mil (0.00025 in.) plastic film was chosen to form a spherical shell 100 ft diam. The sphere will be placed into orbit in a folded condition and then inflated by approximately 1 lb of gas contained at high pressure in a small tank or by the vapor pressure of water or some other liquid. The plastic would thus weigh about 60 lb, and some margin would remain for the weight of seams, the container, and the inflating gas or vapor. Clear plastic does not meet the first three requirements regarding radiation. It can be shown that pigmented plastic of a light color, if it were available, would meet the visibility and thermal requirements but not the others. Plastic coated with aluminum paint would meet the four radiation requirements, but the weight would be too great. Accordingly, a thin film of vapor-deposited aluminum was chosen as probably being the best practical solution to the problem.

NOMENCLATURE

The following nomenclature is used in the paper:

- a = albedo of earth
- A = absorptivity (fraction of incident radiant energy which is absorbed)
- c = velocity of light
- C_S = solar constant
- D = diameter
- h = altitude
- I = intensity of radiation
- k = $R_E/(R_E + h)$
- m = stellar magnitude
- r = distance
- R = reflectivity (fraction of incident radiant energy which is reflected)
- radius

[1] This and other pneumatically erectable configurations were proposed by Mr. W. J. O'Sullivan of the NASA Langley Research Center.

A-1

S = surface area

t = thickness

T = transmission (fraction of incident radiant energy which is transmitted)

= temperature

β = angle of emission and of incidence in Fig. 4

ϵ = emissivity

θ = angle of incidence

κ = extinction coefficient

λ = wave length

μ = permeability

σ = electrical conductivity

= Stefan - Boltzmann constant, $8.135 \times \frac{10^{-11} \text{cal}}{\text{cm}^2 - \text{min} - {}^{\circ}\text{K}^4}$

ϕ = angle of reflection or emission

Subscripts

E = earth

O = initial

S = solar

CS = coldest spot

HS = hottest spot

o = outside

i = inside

REFLECTION OF VISIBLE RADIATION

The point of departure for making a choice of thickness for the aluminum film was data on its reflectivity in the visible. The data that were used are those shown in Fig. 1, which shows experimental results published by Holland (1).[2] This figure shows the reflectivity and the transmission for 4600-A radiation as function of thickness of film and are sufficiently applicable to solar radiation, which has a rather narrow and high maximum at about 4700 A. At a thickness of 375 A the transmission is very nearly zero and the reflectivity 0.9.

These data were, of course, obtained on films produced in the laboratory by a very carefully controlled process and that were very clean. Because the film on the satellite would be commercially deposited and would be subjected to handling in the process of assembling, folding and packaging, and to allow for non-uniformities in film thickness, the thickness chosen for use on the satellite was nearly six times 375 A, or 2200 A. (The mass of aluminum on a 100-foot sphere would thus be 4 lb.) The reflectivity in the visible of the satellite material was measured as 0.90.[3]

[2] Underlined numbers in parentheses designate References at end of paper.

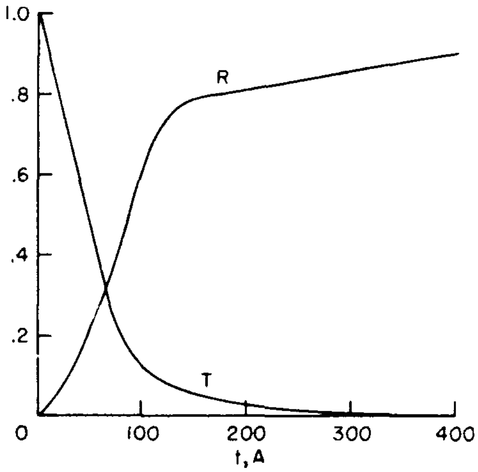

Fig.1 Reflectivity and transmission at 4600A of aluminum films as function of thickness. Data from Reference 1.

The question then is, what will be the visual magnitude of a 100 ft aluminized sphere at an altitude of 1000 miles and illuminated with sunlight. The sphere will intercept sunlight by its projected area and will specularly reflect equally into essentially a complete sphere which has a radius at the earth's surface of the altitude of the satellite. The sun's brightness will therefore be attenuated in the ratio of the projected area of the satellite multiplied by the reflectivity to the surface area of the sphere, or a factor of 2.02×10^{-11}. The apparent visual brightness of the sun expressed as stellar magnitude is -26.7, and since each unit change in magnitude changes the brightness by a factor of $(100)^{1/5}$,

$$(100)^{1/5\,(-26.7 - m)} = 2.02 \times 10^{-11}$$

where m is the visual magnitude of the satellite. From this equation, m = 0.04. The satellite will therefore be brighter than all but two stars, Sirius in the northern hemisphere and Canopus in the southern, and four planets, Venus, Jupiter, Mars and sometimes Saturn.

REFLECTION OF RADAR

It is well known that, as the wave length of the incident radiation increases, the reflectivity of bulk metal generally increases and

[3] These measurements were made for the NASA through the courtesy of Dr. Georg Hass of the Army Engineer Research and Development Laboratories and I. Nimeroff of the National Bureau of Standards.

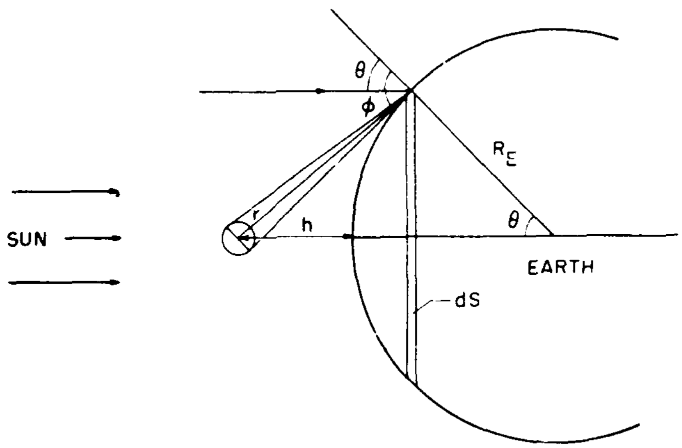

Fig.2 Sketch used in deriving expressions for flux received by satellite.

closely approaches unity in the mid-infrared where reflection depends on only the free and not the bound electrons. A metal can therefore be expected to reflect nearly 100 per cent in the radar region This is true also for a metallic film despite the fact that, although the thickness of the metal may be of the order of a wave length in the infrared, it will be about five orders of magnitude smaller than a wave length in the radar region. This point is mentioned because a number of the people who were interested in the use of this satellite as a reflector of radar signals felt that the thickness of metal was too small for the absorption to be significant and that therefore the signals could not be reflected. It is true that the absorption is not large. The decay of intensity in the metal is given by

$$I/I_0 = e^{-4 \pi \kappa t/\lambda}$$

where the extinction coefficient κ is given by $(\mu \sigma \lambda c)^{1/2}$ for great enough wave lengths (mid-infrared or greater). For the film in question, the conductivity was measured as 4×10^6 mho/m. (This is about 1/9 the value for the bulk metal.) For 10-cm radar, the intensity therefore decreases only to 70 per cent of the initial value in the metal. But the initial value is only two per cent of the incident, as will be shown shortly. Therefore, the absorption is quite small. Large absorption, however, is not necessary for high reflectivity, only a large extinction coefficient is necessary. It can be shown from the boundary conditions which the electric and the magnetic vectors must satisfy, as deduced from Maxwell's equations, that, provided λ and σ are high enough (as they are in this case), the reflectivity of a metal is given by

$$R \approx 1 - 2/\kappa$$

This relation gives in the present case a reflectivity of essentially unity. This was substantiated by measurements, as follows:

Source	Frequency, Mc/sec	Reflectivity R
MIT Lincoln Lab.[a]	2880	0.98
Bell Tel. Labs.[b]	4000	>0.98
Bell Tel. Labs.[b] . . .	11000	>0.98
NASA Langley Res. Cen..	20000	0.97

[a] This measurement was made for the NASA through the courtesy of Dr. D. E. Dustin of the Lincoln Laboratory, Lexington, Mass.

[b] These measurements were made for the NASA through the courtesy of Dr. J. R. Pierce, Director of Electronics Research, Bell Telephone Laboratories, Murray Hill, N. J.

The aluminum skin of the satellite is therefore a good reflector of radar. A sphere, however, is not a very good configuration for a reflector. The minimum transmitter power required for receiving intelligible signals reflected from the satellite depends of course on the kind of information that is to be transmitted, but the approximate transmitter power required for very simple systems and for systems of modulation that require much greater signal-to-noise ratios can be calculated. For transmitting and receiving antennas of 50 ft diameter, a wave length of 10 cm and a satellite diameter of 100 ft and altitude of 1000 miles, if a maximum allowable loss of 100 db per milliwatt is assumed, 10 kw of transmitter power are required. If a maximum allowable loss of 70 db per milliwatt is assumed, 10 megawatts of transmitter power are required. These two transmitter powers fairly well bracket the range of power that might be needed for successfully using the satellite as a reflector.

TRANSMISSION OF ULTRAVIOLET

The ultraviolet region extends from 4000 A to about 300 A. Data on the extinction coefficient κ for aluminum films could be found in the literature only for 4000 A, where κ is given as 3.92 in reference (2). About 10^{-1} of the incident radiation at this wave length is reflected and only about 10^{-13} is transmitted through the aluminum to the mylar. As the wave length decreases, the reflectivity decreases and

the transmission increases. From data given in reference 3 the transmission would be expected to be somewhat less than 10^{-3} in the range from 1250 to 833 A, which includes the wave length of the H_{α} line, 1216A, which is rather intense in solar radiation (4).

Data for the region between 900 and 300 A are very scarce. Reference 3 shows, however, that the transmissivity of a film increases rapidly from nearly zero at 833 A to large values at 500 A and that the reflectivity falls to zero at 700 A and remains zero to the limit of the tests, which was 500 A. The absorption coefficient at 500 A is given as about 10^5 cm^{-1}, so the transmitted intensity is about 10 per cent of the incident.

To sum up, practically no ultraviolet between 4000 A and about 833 A would be expected to reach the plastic, but at about 500 A about 10 per cent would penetrate to the plastic. At this wave length the intensity of the sun's radiation is not yet known. The effect of prolonged exposure of the plastic to about a tenth of this intensity in this wavelength range is also not known.

EQUILIBRIUM TEMPERATURES

The maximum and the minimum allowable temperatures of the skin are set by the properties of the plastic. The temperatures of the portions of the sphere that assume the extreme values are therefore of most interest. Two simplifications that are quite justified make the calculations easier than they otherwise would be. On account of the very small skin thickness, the transfer of heat from the hotter to the colder regions of the sphere by conduction is negligible, and on account of the small heat capacity of the satellite, the time required closely to approach thermal equilibrium is small compared to a half period of revolution.

There are three sources of the radiation that is received by the satellite:

1 Direct radiation from the sun,
2 Sun's radiation reflected from the earth,
3 Direct radiation from the earth.

Direct Radiation From Sun

The solar constant C_S is the amount of radiant energy from the sun that falls on unit area at normal incidence in unit time at a location just above the earth's atmosphere at the average sun-earth distance. Of this flux, a fraction given by A_S is absorbed. (The fact that A_S may be a function of angle of incidence is not taken into account herein.) Therefore the rate at which energy is received directly from the sun by the satellite is

$$(\pi/4)D^2\ C_S\ A_S \text{ cal/min}$$

The Smithsonian value of the solar constant is 1.94 cal/cm^2-min (5). A later and perhaps more accurate value is 2.00 $\pm$ 0.04 cal/cm^2-min (6). The annual variation of incident flux between a maximum in December and a minimum in June is an additional 0.07 cal/cm^2-min. The value used herein for the flux is the mean,

$$C_S = 2.00 \text{ cal/cm}^2\text{-min.}$$

Solar Radiation Reflected From Earth

If the earth were a specular reflector of sunlight, the calculation of the rate of reception by the satellite of solar radiation reflected from the earth would be relatively simple. The reflection, however, probably occurs principally from clouds and is therefore diffuse rather than specular. Russel (7) derived an expression for the diffuse case that is applicable when the receiving body is at a distance from the reflector that is large compared to the radius of the reflector. The same expression is also derived in (8). The results are not applicable when the receiver is close to the reflector. Gast (9) treats the case when the satellite is less than several thousands of miles from the earth and gives an expression that is through error just one half that obtained herein as an approximate expression.

The energy absorbed per unit time per unit area normal to the direction of propagation, by reflection from an element of area dS on the earth is, by Lambert's law, and Fig. 2,

$$\int C_S\ A_S\ a \cos\theta \cos\phi\ dS/\pi r^2$$

The element of area dS on the earth is

$$dS = 2\,\pi\,R_E^{\,2} \sin\theta\ d\theta$$

From the cosine law, the distance r is given by

$$r^2 = R_E^{\,2} + (R_E + h)^2 - 2\,R_E\,(R_E + h)\cos\theta$$

or

$$r^2 = (R_E + h)^2\,(1 + k^2 - 2\,k\cos\theta)$$

where

$$k = R_E/(R_E + h)$$

From the sine law,

$$\cos\phi = \left[1 - \frac{1}{\csc^2\theta\,(\cos\theta - k)^2 + 1}\right]^{1/2}$$

$$= \frac{\cos\theta - k}{(1 + k^2 - 2\,k\cos\theta)^{1/2}}$$

The projected normal area of the satellite is $(\pi/4)D^2$. Since the radiation is essentially solar, the absorptivity of the satellite for it is taken as A_S. Then the flux absorbed by the satellite is

$$\frac{\pi D^2}{4}\, C_S\, A_S\, a2K^2 \int_{\theta=0}^{\theta=\text{arc cos } k} \frac{(\cos\theta - k)\cos\theta\sin\theta\, d\theta}{(1 + k^2 - 2\,k\cos\theta)^{3/2}}$$

which has the value

$$\frac{\pi}{4}\, D^2\, C_S\, A_S\, a\, \frac{4}{3k}\left[1 + \frac{k^3}{2} - \left(1+\frac{k^2}{2}\right)(1-k^2)^{1/2}\right] \text{cal/min}$$

The factor $\frac{4}{3k}\left[\quad\right]$ can be very closely approximated by

$$2\left[1 - (1 - k^2)^{1/2}\right]$$

Therefore the satellite receives from the earth as diffusely reflected sun's radiation

$$\frac{\pi}{4}\, D^2\, C_S\, A_S\, a\, 2\left[1 - (1 - k^2)^{1/2}\right] \text{cal/min} \quad (1)$$

Direct Radiation From Earth

Since the earth remains at nearly the same temperature for centuries, and the outward flow of energy from the interior is very small and the net energy used by plants is very small, practically all the energy the earth receives from the sun is either reflected or radiated. The surface area of a sphere is four times the projected area. The radiation from the earth is therefore

$$C_S\,(1 - a)/4 \text{ cal/cm}^2\text{-min}$$

The flux falling on and absorbed by the satellite is, by Lambert's law and figure 2,

$$C_S\, A_E\, \frac{1 - a}{4}\, \frac{\pi D^2}{4} \int_{\theta=0}^{\theta=\text{arc cos } k} \frac{\cos\phi}{\pi\, r^2}\, dS \text{ cal/min}$$

When the same substitutions as before are made and integration is performed, the flux becomes

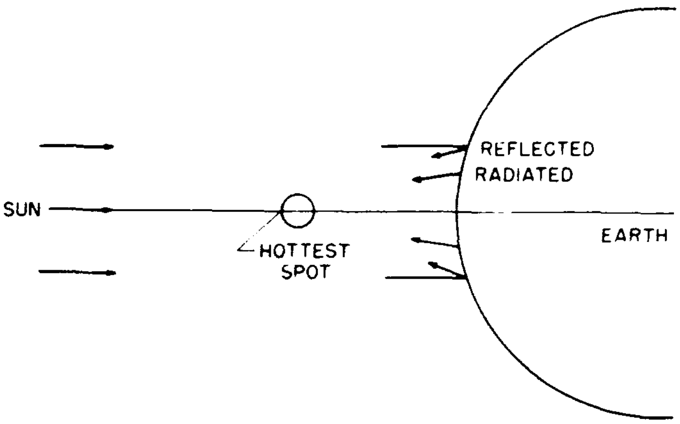

Fig.3 Location of hottest spot on satellite.

$$\frac{\pi}{4}\, D^2\, C_S\, A_E\, \frac{(1 - a)}{2}\left[1 - (1 - k^2)^{1/2}\right] \text{cal/min} \quad (2)$$

Temperatures

The total rate of energy reception is therefore

$$\frac{\pi}{4}\, D^2\, C_S\, A_S \left\{1 + 2\left[a + \frac{1 - a}{4}\frac{A_E}{A_S}\right]\left[1 - (1 - k^2)^{1/2}\right]\right\} \text{cal/min} \quad (3)$$

The total rate of energy loss is $\pi D^2 \epsilon_0 \sigma T^4$ cal/min where T^4 is the fourth power of the skin temperature averaged over the surface in such a way that the above expression is the rate of radiation from the satellite. At equilibrium, rates of energy reception and loss are equal:

$$\epsilon_0\, \sigma T^4 = \frac{1}{4}\, C_S\, A_S \left\{1 + 2\left[a + \frac{1 - a}{4}\frac{A_E}{A_S}\right]\left[1 - (1 - k^2)^{1/2}\right]\right\} \text{cal/cm}^2 \text{ min} \quad (4)$$

The results of the foregoing analysis are used first to derive an expression for the equilibrium temperature T_{HS} of the hottest spot on the satellite when the satellite is so located that this temperature is a maximum; i.e., that energy reception rate is greatest. The satellite of course is then directly between the sun and the earth (Fig. 3). For unit area of the hottest

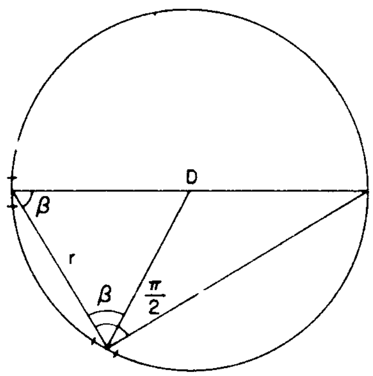

Fig.4 Geometrical relations in a circle.

spot facing the sun, the thermal balance is given by the equation

Reception from sun + reception from inside = radiation from both sides

The rate of reception from the sun is $C_S A_S$.

The rate of radiation from both sides is $(\epsilon_i + \epsilon_o)\ \sigma\ T^4_{HS}$.

The rate of reception from the inside of the satellite must next be found. Because the skin of the satellite is so thin that no significant temperature difference can exist between the outside and the inside surfaces, equation (4) can be multiplied by ϵ_i / ϵ_o and the surface area $(\pi/4)D^2$ to obtain the total rate of emission of radiation on the inside of the sphere:

$$\frac{\pi}{4} D^2\ \epsilon_i\ \sigma\ T^4 = \frac{\pi D^2}{16} \frac{\epsilon_i}{\epsilon_o} C_S\ A_S \left\{ 1 + 2 \left[a + \frac{1-a}{4} \frac{A_E}{A_S} \right] \left[1 - (1 - k^2)^{1/2} \right] \right\} \quad (5)$$

It is easy to show, however, that this flux is received equally by all elements of area on the inside surface of the sphere.

Any two elements of area on the surface of a sphere, Fig. 4, lie on a great circle plane through the sphere center. The intensity of the radiation from one of these elements is by Lambert's law proportional to cos β. The normal projection of the receiving element is proportional to cos β. The intensity also varies inversely as the square of the distance r between the elements. But in a circle, $r = D \cos \beta$. Therefore, the flux received by an element from another element does not depend on β and is therefore not a function of latitude or azimuth. In other words, a given element of area contributes equally to the flux received by all other elements. Therefore all elements receive energy at the same rate, no matter what the temperature distribution is. This result is, of course, true only for a sphere.

Therefore, the rate of reception of energy by unit area of the hottest spot is just $\epsilon_i\ \sigma\ T^4$ as given by equation (5). Then in equilibrium, the thermal balance equation for unit area of the hottest spot is

$$C_S\ A_S + \frac{1}{4} \frac{\epsilon_i}{\epsilon_o} C_S\ A_S \left\{ 1 + 2 \left[a + \frac{1-a}{4} \frac{A_E}{A_S} \right] \left[1 - (1 - k^2)^{1/2} \right] \right\}$$

$$= (\epsilon_i + \epsilon_o)\ \sigma\ T^4_{HS} \quad (6)$$

An expression is needed also for the temperature T_{CS} of the coldest spot on the satellite when the satellite is in the location that T_{CS} is a minimum; i.e., when the satellite is in the earth's shadow. It then receives no direct or reflected energy from the sun, only direct radiation from the earth. From equation (4) the thermal-balance equation for the satellite when it is in the earth's shadow is

$$\epsilon_o\ \sigma\ T^4 = \frac{1}{4} C_S\ A_S \left(\frac{1-a}{2}\right) \frac{A_E}{A_S} \left[1 - (1 - k^2)^{1/2} \right] \quad (7)$$

The coldest spot receives energy only by radiation from the inside surface of the satellite, at the rate

$$\epsilon_i\ \sigma\ T^4 = \frac{1}{4} \frac{\epsilon_i}{\epsilon_o} C_S\ A_S \left(\frac{1-a}{2}\right) \frac{A_E}{A_S} \left[1 - (1 - k^2)^{1/2} \right] \quad (8)$$

Its thermal balance is therefore given by

$$\frac{1}{4} \frac{\epsilon_i}{\epsilon_o} C_S\ A_S \left(\frac{1-a}{2}\right) \frac{A_E}{A_S} \left[1 - (1 - k^2)^{1/2} \right]$$

$$= (\epsilon_i + \epsilon_o)\ \sigma\ T^4_{CS} \quad (9)$$

What remains is to substitute values for the various constants into equations (6) and (9)

and to solve for T_{HS} and T_{CS}. The value of A_S for the satellite material was measured as 0.10.[4] The value of ϵ_0 was found to be 0.05.[5] The quantity A_E can be assumed to have the same value as ϵ_0. The emissivity ϵ_1 of the mylar side or inside surface of the satellite material was found to be 0.40.[6] Danjon (10) has been investigating the earth's albedo since 1926 by measuring the intensity of the earth-shine reflected by the moon. Fritz (11) has computed the earth's albedo from measurements and estimates of the individual albedos of clouds, seas, and so on. They both agree that the average value is about 0.36. There is evidence of a minimum value of about 0.32 in July and a maximum value of 0.52 in October.

Calculations of the satellite's highest temperature were made by equation (6) for both the average and the maximum values of albedo, and for perigee altitudes of both 800 and 1000 miles, for which k is, respectively, 0.833 and 0.80. The results are shown in Table 1.

Table 1 Temperature of Hottest Spot on Satellite for Two Values of Altitude and Two of Earth's Albedo

Altitude, miles	Earth's albedo, a	T_{HS}, deg C
800	0.36	150
800	0.52	160
1000	0.36	148
1000	0.52	156

The temperature of the coldest spot on the satellite should properly be calculated only for the average value of the albedo. Its value from equation (9) is -104 C for an altitude of 800 miles and -108 C for an altitude of 1000 miles.

These calculated maximum and minimum values of the temperature are believed to be acceptable.

[4] Measurements of this quantity were made for the NASA through the courtesy of G. Hass of Army Engineer Research and Development Laboratories and of I. Nimeroff of the National Bureau of Standards.

[5] Measurements of this quantity were made for the NASA through the courtesy of L. F. Drummeter and E. Goldstein of the Naval Research Laboratory and of T. O. Thostesen of the Jet Propulsion Laboratory.

[6] Measurements of this quantity were made for the NASA through the courtesy of L. F. Drummeter and E. Goldstein of the Naval Research Laboratory and of T. O. Thostesen of the Jet Propulsion Laboratory.

Limited tests have shown that no detectable changes occur in the aluminized plastic when heated to 230 C in an inert gas, although the tensile strength of the plastic is zero at 245 C. Tests have also shown that seams such as will be used in constructing the sphere are satisfactory at -100 C so far as adhesive properties and flexibility are concerned.

CONCLUSION

The design study of the characteristics, with respect to radiation, of a 100-foot diameter hollow spherical satellite formed of 1/4-mil mylar and coated with 2200 A of vapor-deposited aluminum has shown that the performance can be predicted to be satisfactory with regard to its visibility, its ability to reflect radar, its maximum and minimum temperatures, and probably its resistance to deterioration by solar ultraviolet.

Acknowledgment

The authors are happy to express their appreciation for the very considerable assistance of Dr. Adolf Buseman, Research Staff Scientist, NASA Langley Research Center, and for the very interesting discussions held with him.

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